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Genomic evidence for the Pleistocene and recent population history of Native Americans.

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How and when the Americas were initially populated remains contentious. Using the largest ancient and modern genome-wide dataset to date, we find that Native American ancestors entered the Americas from Siberia no earlier than 23 thousand years ago (KYA), with subsequent gene flow between them and East Asians. We find that Native Americans diversified into two basal genetic branches about 13 KYA; one is currently represented in both North and South America while the other appears restricted to North America. We further find some evidence for a secondary gene flow into some Native Americans from populations sharing ancestry with Australo-Melanesians that we hypothesize may have been transmitted through populations represented by Aleutian islanders. Contrary to a number of recent claims, we find that there was no long-term isolation of early Americans in Beringia, that Amerindian and Athabascan ancestors entered the Americas at the same time, and that present-day South Americans are not related to modern Australo-Melanesians.

The peopling of the Americas has been a topic of research for more than a century (1). Despite this, questions regarding when and from where humans entered the Americas remain mired in controversy. The long-term view among archaeologists that humans first arrived in the Americas no earlier than *ca.* 13 KYA (the Clovis-first model) (2) has been seriously questioned in recent years with archaeological sites dating one-two thousand years older than Clovis (3-6), while claims of archaeological sites predating the Last Glacial Maximum (*ca.* 20 KYA) (*e.g.* 7-10) remain controversial. Molecular-based studies of mitochondrial DNA (mtDNA) and Y-chromosome markers have suggested that humans first entered the Americas between 15-23 KYA (11-16). However, these broad estimates are limited due to the use of single, uniparentally inherited loci.

Linguistic, dental and genome-wide data from contemporary individuals have suggested that Native Americans, represented by Amerindians and Athabascan speakers, have separate times of entrance into the Americas (17-19). By contrast, studies based on mtDNA and Y-chromosome data have argued for one founding migration for all Native Americans (*e.g.* 20-24). Similarly, some argue for an isolation period for Native American ancestors in Siberia prior to entering the Americas, possibly for as long as 15,000 years (Beringian Incubation Model) (11, 25, 26), while others have questioned this, arguing for continuity between Beringian and other Eurasian populations (15).

While the predominant view is that ancestors of Native Americans were the first humans to enter the Americas, some claim an early migration to the Americas from Europe (Solutrean model) (27) or from populations with recent shared ancestry with Australo-

Melanesians (Paleoamerican model) (28-33). Recent ancient genetic evidence has largely put the Solutrean model to rest (34, 35), while the Paleoamerican model based on skull morphology remains to be properly assessed using genomic approaches.

In this study, we address these unresolved paradigms relating to the early peopling of the Americas by using the largest genome-wide dataset to date from present-day and ancient individuals from North and South America, Siberia, East Asia, South East Asia and Oceania. We focus our study on the population history of the Native Americans, since a previous study has already addressed the early peopling of the American Arctic (36).

Dataset

We sequenced 31 present-day genomes from the Americas, Siberia and Oceania to an average depth of *ca.* 20X: Siberians – Altai (n=2), Buryat (n=2), Ket (n=2), Koryak (n=2), Yakut (n=2), Siberian Yupik (n=2); North American Native Americans – Tsimshian (n=1); South/Central American Native Pima (n=1), Huichol (n=1), Aymara (n=1), Yukpa (n=1); Oceanian – Papuan (n=14) (supplementary text S1, Table S1) (37). We additionally sequenced to low depth (0.003X to 1.7X), 23 ancient genomes dating between ~0.2-6 KYA from North and South America (supplementary text S1, Table S5). We further generated single nucleotide polymorphism (SNP) array data from 61 present-day individuals from 27 populations, including Native Americans and Siberians that have limited representation in the genomic literature (supplementary text S1, Tables S3, S4). These datasets were analyzed together with previously published genome and SNP chip

data (Tables S1, S3, S4). We masked for recent European admixture in some Native American populations prior to downstream analyses (supplementary text S5).

Time of entrance into the Americas

We first used *TreeMix* (38) to estimate the structure of the admixture tree relating American populations to worldwide populations (Figs. 1, S5, supplementary text S6). We found all Native Americans to be a monophyletic group, with further diversification into two basal branches, one representing Amerindians and the other representing Athabaskan speakers. We found the Paleo-Eskimos and Inuit to be a separate clade to the Native Americans, as reported previously (36).

Next, we estimated divergence times between Native Americans and East Asians by applying *diCal2.0* (supplementary text S7), a new version of the method *diCal* (39) extended to handle complex demographic models involving multiple populations with migration (40), and an identity-by-state (IBS) tract method (41) (supplementary text S7) on high-coverage whole genome datasets. As we identified the Siberian Koryak to be one of the closest sampled East Asian populations to the Native Americans using *TreeMix* (Figs. 1, S5), we first determined the statistical estimates of divergence times between Native Americans and Koryak. We considered demographic models that reflected a clean split as well as gene flow post-dating the split between population pairs (Fig. 2A). Using both *diCal2.0* and IBS tracts we dated the divergence of Native Americans, including Amerindians and Athabascans, to Koryak to be close to 20 KYA, or perhaps slightly

older but no more than 23 KYA (Figure 2B, supplementary text S7). We also found that the models that include gene flow between the population pairs provided a better fit to the data (Fig. 2B, supplementary text S7). We used the Multiple Sequentially Markovian Coalescent (MSMC) method (42) (supplementary text S7) to estimate relative cross coalescence rates (CCR) between pairs of individuals. Overall, simulations based on the model estimates obtained using *diCal2.0* and real data show very similar relative CCR and IBS tract length distributions, which serves as an independent confirmation for *diCal*'s model estimates (Fig. 2C, D). We evaluated all methods using simulations under complex demographic models, and taking switch-errors in haplotype phasing into account (supplementary text S7).

We then proceeded to utilize *diCal2.0* with the model that allows for gene flow between populations after their split to estimate divergence times for Native Americans from more distant East Asians, namely the Siberian Nivkh and Han Chinese. The estimates for both Amerindians and Athabascans were again very similar to one another, *ca.* 23 KYA (supplementary text S7), suggesting that Amerindian and Athabascan belong to the same migration source. This was further supported by a spatially explicit population genetics model in which local demography is driven by paleo-climate and paleo-vegetation reconstructions (Fig. 3, supplementary text S8) (43). In all cases, we found that gene flow between Siberian and Native American populations is required to provide good fits of the models to the IBS tract distribution and relative CCR by MSMC. Moreover, we found strong evidence for gene flow between Athabascans and the Inuit (Table S11B), which is also supported by *TreeMix* (38) (supplementary text S6, Fig. S5), *D*-statistics employing

both sequencing and genotyping data (44-46) (supplementary text S6, Fig. S6A, Fig. S8) and, outgroup f_3 statistics (34, 46) (supplementary text S6, Fig. S12). We note that while we attempted to estimate the divergence times for Inuit-Siberians and Inuit-Native Americans (supplementary text S7, Table S11, Figs. S19, S25-27), our analyses are complicated by the extensive gene flow between Inuit and the Athabascans as well as complex admixture between Siberians and American Arctic groups (supplementary text S6, Figs. 1, S5). Additionally, all our estimates are based on assumptions regarding mutation and recombination rates. There is still some debate regarding human mutation rates and this uncertainty could affect our results (47).

Together, these results support a common Siberian origin for all Native Americans and their isolation and entrance into the Americas no earlier than 23 KYA, but with subsequent admixture with East Asian populations. This additionally suggests that Mal'ta-related admixture into the early Americans (34), representing ancestors of both Amerindians and Athabascans (Fig. 1), occurred sometime after 23 KYA, after the Native Americans split from East Asians. When we introduced stopping time of gene flow as a free parameter in the *diCal2.0* analysis, we still obtained the highest likelihood for a divergence time of 22 KYA for both Amerindians-Siberian and Athabascans-Siberian pairs, but the two pairs differed in the estimated gene flow rate and stopping time of the gene flow (supplementary text S7, Table S11C). Gene flow between Athabascan and Siberian seems to have stopped *ca.* 12 KYA, while we found evidence for comparatively weaker gene flow until recently (*ca.* 2 KYA) between at least some East Asian populations and some Amerindian groups. Contributing factors may include

gene flow from Inuit into Siberians, although an indirect East Asian signal in South Americans cannot be discounted.

Diversification within the Americas

Using *diCal2.0*, we also estimated that Athabascans and Amerindians diversified *ca.* 13 KYA, which is also consistent with MSMC results (supplementary text S7, Table S11B), further supporting a common entrance of the two groups into the Americas after their split from Siberians after 23 KYA. We additionally employed outgroup f_3 statistics (34, 46) to determine the genetic affiliations of ancient and modern samples within the Americas (supplementary text S6, Figs. 4, S13, S14). We found that there was a marked differentiation in the Native American gene pool at least by the end of the Clovis tradition, *ca.* 12.6 KYA, with one branch representing Native Americans from both North and South America and the other being restricted to North America (Figs. 4, S13, S14). Moreover, using a large SNP chip panel masked for non-Native ancestry with increased representation of northern Amerindians, we observed a signal of gene flow between not only the Athabascans and the Inuit, as discussed before, but also between the Inuit and northwest Amerindians residing in the same region as the northern Athabascans (supplementary text S6, Fig. S8). This signal was not detected in north-central or northeastern Amerindian populations and provides a possible explanation for the southern Amerindians being genetically closer to the north-central and northeastern Amerindians than to the Athabascans and northwestern Native Americans.

In contrast to the Pleistocene human from Anzick-1, all the Holocene individuals from the Americas tend to be related to present-day populations from the same geographical regions (Figs. 4, S13, S14). As such, our results suggest that the diversification of Athabascans and Amerindian groups happened within the Americas. The data also point to a degree of geographic continuity of ancient and modern populations over, at least, the last 5 KYA.

Australo-Melanesian gene flow into the Americas

When testing for gene flow between Athabascans and Inuit using masked SNP chip based *D*-statistics (46), we observed a weak gradient in the *D*-statistic values across the Americas (Fig. S8). There is a tendency for the Inuit to be much closer to the Athabascans, than to certain Amerindians like the Arhuaco, Algonquin, Cree and Yaqui when compared to other Amerindians such as Palikur and Surui (Fig. S8). To further investigate this trend, we tested for additional gene flow from Eurasian populations into parts of the Americas using *D*-statistics (46). Using the masked SNP chip dataset with multiple Native American populations, we found that some American populations, including the Aleutian Islanders, Surui from Brazil and the Athabascans are closer to Australo-Melanesians than other Native Americans such as North American Ojibwa, Cree and Algonquin and South American Purepecha, Arhuaco and Wayuu (Fig. S10). Surui is one of closest Native American populations to Australo-Melanesians including Papuans, non-Papuan Melanesians, Solomon Islanders, and South East Asian hunter-gatherers such as Aeta. While we note that our results show only weak trends, they

nevertheless suggest a possible scenario leading to a Eurasian signal in some Native Americans that is related to Australo-Melanesians and East Asians.

Based on both archaeological evidence and mtDNA data from ancient and modern samples, the Aleutian Islands are hypothesized to have been colonized as early as *ca.* 9 KYA by ‘Paleo-Aleuts’ who were succeeded by the ‘Neo-Aleuts’, with present-day Aleutian Islanders potentially resulting from admixture between these two streams (48, 49). While Aleutian Islanders were previously found to be closely related to the Inuit (36), their increased affinity to East Asians and Oceanians compared to the rest of the Americas suggests a possible ‘northern’ route for the spread of an Oceanian signal into some Native Americans. Using enhanced D-statistics on whole genomes (50), we again found some evidence for more Papuan and Denisovan ancestry in the Aleutian Islander than in the Native American samples (supplementary text S6, Table S10). The differential affinity of Native Americans to Oceanians, ranging from a strong signal in the Surui to much weaker signal in northern Amerindians such as Ojibwa, points to this signal coming into the Americas after the initial peopling by Native American ancestors. This is also supported by the results from the *diCal2.0* and MSMC analyses showing a weak but recent gene flow into South Americans from populations related to contemporary Northeast Asians, which might be considered a proxy for the related Aleutian Islanders (Fig. 2). However, how this signal ultimately reached South America remains unclear, but one possible route could be through the Athabascan expansion southwards that might have brought with it an indirect Oceanian signal through the Aleutian Islanders. Additionally, we caution that all results are based on analyses of a small fraction of the

Aleutian Islanders datasets (masked SNP chip and whole genome data), and this may bias the results in an unforeseen manner.

The Paleoamerican model

To further test if the Australo-Melanesian gene flow could provide support for the Paleoamerican model, we used ancient genomes from groups (Pericúes from Mexico and the Fuego-Patagonians from Chile and Argentina) that, based on their distinctive skull morphologies, are claimed to be ancient relicts of Paleoamericans (28, 51-53). Using Principal Component Analysis and ADMIXTURE (54), we show that the ancient samples cluster with other Native American groups and outside the range of Oceanian genetic variation (supplementary text S10, Figs. S32, S33, 34). Similarly, outgroup f_3 statistics (34, 46) reveal low shared genetic ancestry between the ancient samples and Oceanians (supplementary text S10, Figs. S36, S37). Furthermore, from genome-based and masked SNP chip data-based D -statistics (44-46), we found no evidence for gene flow into the Pericúes from Oceanians, but observed the Fuego-Patagonians to have at least some signal from Oceanian groups (supplementary text S10, Fig. 39).

As the Paleoamerican model is based on cranial morphology (28, 51-53), we also measured craniometric data for the ancient samples (supplementary text S10). We assessed their phenotypic affinities to supposed Paleoamericans, Amerindians and worldwide populations using more recently accepted methodologies (supplementary text

S10, Fig. S41). The majority of the studied samples show close craniometric affinities to present-day populations from North America, the Arctic, and East Asia (Fig. S41), implying that previous reporting of the close similarity of Paleoamerican and Australo-Melanesian cranial morphologies could not be replicated (30). Admittedly, our morphometric analyses show that these ancient samples are not true Paleoamerican relicts as claimed, and hence do not support the Paleoamerican model. Regardless, our genomic data provide no support for an early migration of populations related to Australo-Melanesians to South America.

Discussion

Overall, our findings suggest that Native Americans had a high level of continuity with Eurasian populations, in particular the northeast Siberians, prior to entering the Americas, and that all present-day Native American populations originated from the same migration with subsequent gene flow from East Asia, including some that relates to Australo-Melanesians. Hence, our results contradict the long-term Beringian incubation model (11, 25, 26) and the dual migration model for the Amerindians and Athabascans (17-19). Moreover, Native Americans diverging no earlier than 23 KYA from East Asians provides an upper bound on the isolation, the entrance date of Native Americans, and the subsequent spread of Native American ancestors into the Americas, although our data are unable to provide exact geographical contexts for these processes. This is also in agreement with the pre-Clovis model suggesting initial occupation of the Americas a few thousand years prior to Clovis (3-6). However,

archaeological sites in the Americas significantly older than the Last Glacial Maximum (*ca.* 20 KYA) (7-10) should, in our view, be treated with caution. We further find a diversification of ancestral Native Americans leading to the formation of a ‘northern’ and ‘southern’ branch, which appears to have taken place within the Americas. As this event coincides roughly with the opening of habitable routes along the coastal and the interior corridors into unglaciated North America some 16 KYA and 14 KYA, respectively (53-56). This suggests a possible role of one or both these routes in the isolation and subsequent dispersal of Native Americans within the Americas.

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Figure legend

Fig. 1. Origins and pre-Columbian admixture history of present-day Native

Americans. A. Our results support a single migration for the ancestors of all present-day Native Americans, including Amerindian and Athabascans speakers (purple). The gradient in colour provides an estimate of the initial divergence of Native American ancestors from the ancestors of present-day East Asians (~23 KYA), northeast Siberians (~20 KYA), and finally their appearance in the Americas ~15 KYA, which is supported by archaeological evidence from sites like Monte Verde (59). Subsequently, ~13 KYA (red), there was a split between the northern and southern branches of Native Americans, with the former comprising Athabascans and northern Amerindians and the latter consisting of Amerindians speakers in Central and South America including the ~12,600-year-old Clovis (35). There is an admixture signal between Inuit and Athabascans and northwestern Amerindians, and between Inuit and Siberians (yellow arrows); however, the gene flow direction is unresolved due to the complexity of the admixture events (SOM). Additionally, we see a weak signal of gene flow from Papuan-related populations into some Native Americans, which may have been mediated through East Asians and Aleutian Islanders. Also shown is the Mal'ta gene flow into Native American ancestors some 23 KYA (Raghavan et al. 2014). We note that it is currently not possible for us to ascertain the exact geographical locations of the depicted events; hence, the positioning of the arrows should not be considered a reflection of these. **B.** Admixture plot, based on *TreeMix* (38) results and supported by *D*-statistics (SOM), shows that all Native Americans form a clade, separate from the Inuit, with admixture between some Native Americans and the North American Arctic.

Fig. 2. Divergence estimates between Native Americans and Siberian Koryak. A.

The demographic model used allows for continuous gene flow between populations 1 and 2, starting from the time T_{DIV} of divergence and ending at T_M . The backward probability of migration per individual per generation is denoted by m . The bottleneck at T_B captures the out-of-Africa event. **B.** The red curves depict empirical distributions of IBS tracts shared between Karitiana-Koryak (solid) and Athabascan-Koryak (dashed). The blue and orange curves depict IBS tracts shared between the two population pairs, simulated under two demographic models based on results from *diCal2.0*. Overall, the migration scenarios (orange) match the empirical curves (red) better than the clean split scenarios (blue), with more long IBS tracts showing evidence of recent common ancestry between Koryaks and Native Americans. **C and D.** Relative CCR for the Karitiana-Koryak and Athabascan-Koryak divergence (red), respectively, including data simulated under the two demographic models in panel B. In both cases, the model with gene flow (orange) fits the data (red) better than the clean split model (blue). The migration model explains a broader CCR tail in the case of Karitiana-Koryak and the relatively late onset of the CCR decay for Athabascan-Koryak.

Fig. 3. Testing migrations into the Americas using a spatially explicit population genetics model. Estimates of differentiation between Central and South American populations versus present-day Athabascan and Greenlandic Inuit, and the ancient Saqqaq and Anzick-1 genomes (black vertical lines), compared to predictions from a Climate-Informed Spatial Genetic model reconstructing a single wave into the Americas (curves, the solid part represents the 95% credibility interval). Both Anzick-1 and the Athabascans were part of the same main wave into the Americas to which other Central

and South American populations belonged to, while the Inuit and Saqqaq are the descendants of different waves (observed values outside the 95% credibility interval).

Fig. 4. Diversification within the Americas. We used SNP chip data-based f_3 -statistics (34,45) of the form $f_3(X, \text{Ancient}; \text{Yoruba})$ to estimate the shared ancestry between Anzick-1 and low coverage Holocene-aged samples from the Americas to a large panel of worldwide populations (X), including previously unrepresented Athabascan and Amerindian groups from North America (Table SX). Individuals from the Americas were masked for non-Native ancestry prior to the analysis. The f_3 statistics are depicted as heat maps with the sampling location of the ancient sample marked by the dotted lines, and corresponding ranked plots with error bars are shown in Fig. SY. We find the Anzick-1 sample to share most ancestry with the ‘southern’ branch of Native Americans when using multiple northern Native Americans sequenced in this study, consistent with (35). The rest of the ancient samples share most ancestry with Native Americans, as expected, with a general tendency to be genetically closer to present-day populations from the same geographical region.

Figure 1

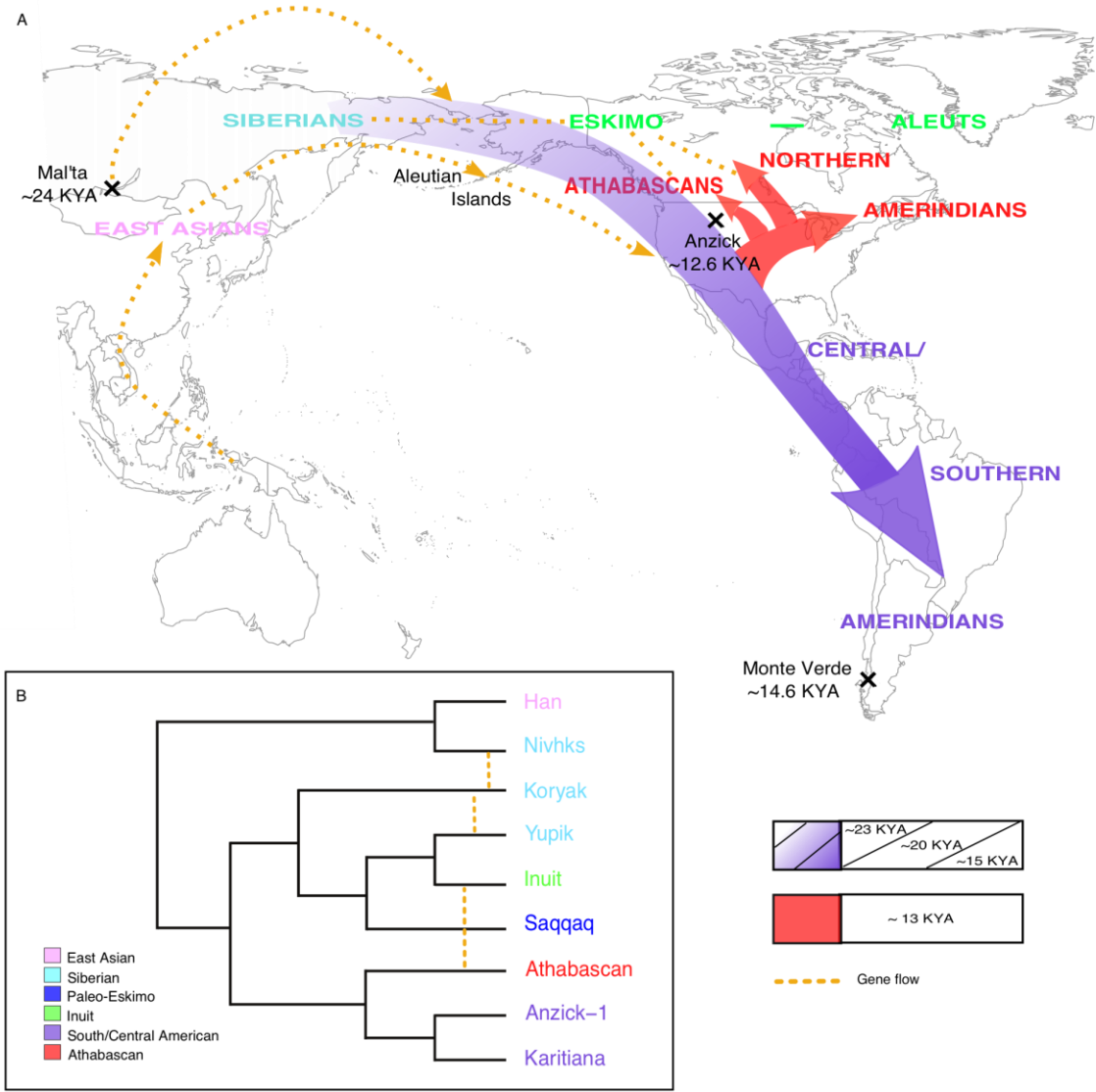


Figure 2

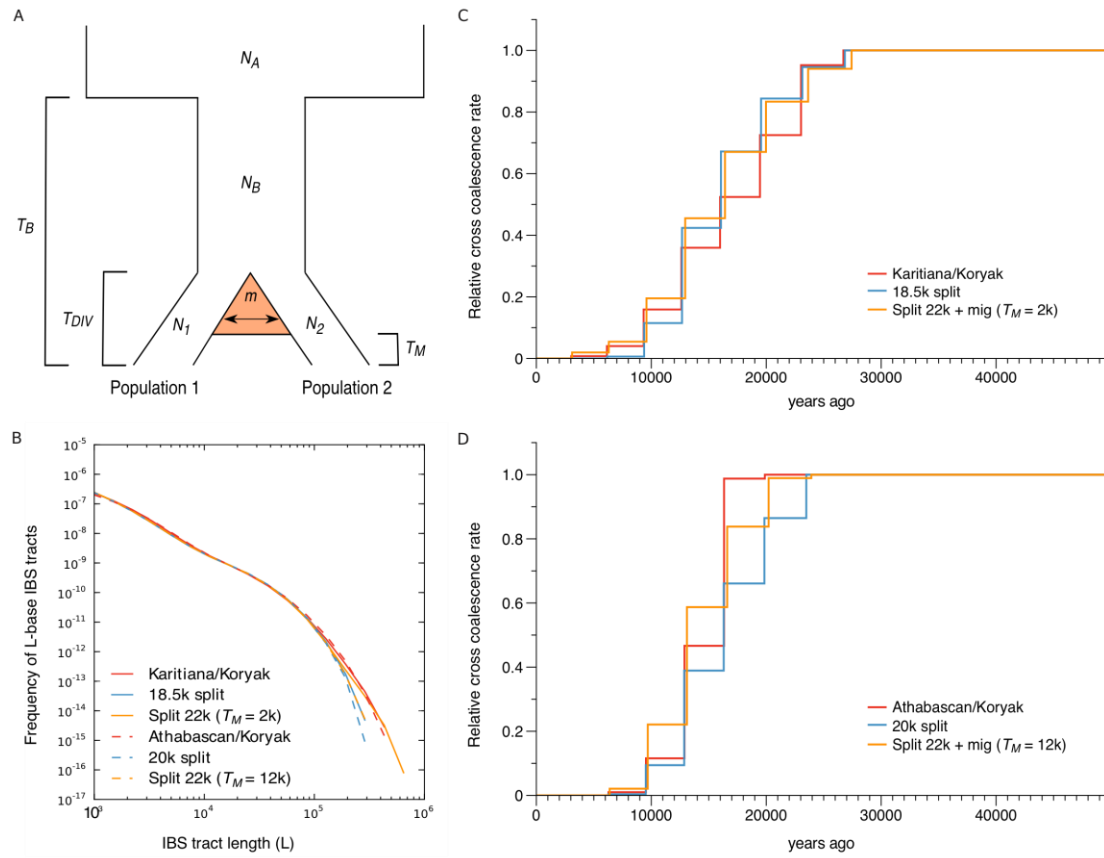


Figure 3

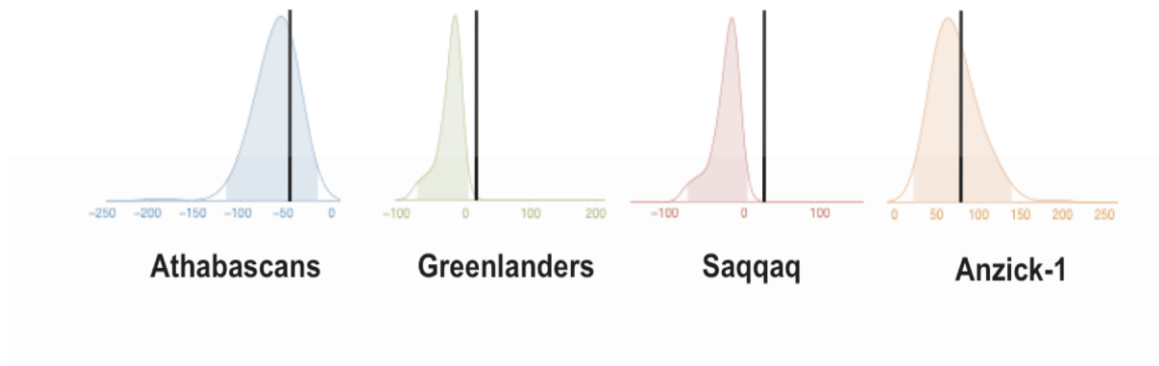


Figure 4

